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GEOACOUSTIC MODELS AND BIOTURBATION

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ABSTRACT

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Two types of geoacoustic models are used to describe relationships between physical and acoustic properties of unconsolidated marine sediments: simple predictive, and theoretical models. Simple predictive models use the apparent correlation between physical properties of sediments (usually porosity, grain size or density) and acoustic properties of sediments to predict velocity and attenuation of compressional and shear waves. Theoretical models use elastic properties of sediments (rigidity, compressibility, etc.) to calculate acoustic properties.

It has been shown that bioturbation by benthic animals profoundly affects the physical properties of marine sediments. Activities including burrowing, ingestion/digestion/defecation, tube building, biodeposition, cementation and metabolic activities modify porosity, grain size, density, fabric, rigidity and compressibility of sediments.

We hypothesize that bioturbation by benthic animals alters acoustic properties of unconsolidated marine sediments. An example is provided for predicted effects of bioturbation on selected acoustic and elastic properties of a silty mud sediment. Knowledge of effects of bioturbation on unconsolidated marine sediments may increase our understanding of the relationship between predicted and measured acoustic properties.

INTRODUCTION

Two types of geoacoustic models are used to describe relationships between physical and acoustic properties of unconsolidated marine sediments: simple predictive, and theoretical models. Simple predictive models use the apparent correlation between physical properties of sediments (usually porosity, grain size or bulk density) and acoustic properties of sediments to predict velocity and attenuation of compressional and shear waves. The correlations are usually presented in graphic form or by regression equations. Porosity, density and grain size are also used to predict bottom loss of compressional waves at normal incidence to the sediment—water interface.

Although disagreement exists as to which elastic or viscoelastic model should be applied to marine sediments (Hamilton, 1971a, 1974a; Stoll, 1974, 1977), there is no disagreement that physical, acoustic and elastic properties of marine sediments are theoretically related and, once measured, can be used to compute one another.

Any process which controls or alters any of the physical or elastic properties also changes the acoustic properties of sediment. Bioturbation (biological modification of sediments) is such a process, and therefore may be important theoretically and heuristically in geoacoustic models.

It is the purpose of this paper to review relevant empirical and theoretical relationships between physical and acoustic properties of marine sediments, as well as the effects of bioturbation on physical properties of sediments, in order to develop a working hypothesis on effects of bioturbation on elastic and acoustic properties of marine sediments.

RELATIONSHIP BETWEEN ACOUSTIC AND PHYSICAL PROPERTIES OF SEDIMENTS

Prediction of acoustic properties of marine sediments from measured, extrapolated or predicted physical properties of sediments is central to the development of geoacoustic models (Hamilton, 1971b, 1974b). Empirical relationships among physical and acoustic properties of sediments have been developed from concurrent measurements of those properties under laboratory conditions, in situ by diver-held or submersible-held probes or from freshly collected piston, gravity or box cores.

The first empirical equations were developed in the 1950's between compressional wave velocity and sediment median (or mean) grain size, porosity and bulk density (Hamilton, 1956, 1963; Hamilton et al., 1956; Sutton et al., 1957; Nafe and Drake, 1957, 1963; and others). The most recently published regression equations between compressional wave velocity and the above mentioned physical properties are those of Hamilton (in: Morris et al., 1978). Different regressions were presented for sediments from the continental terrace (shelf and slope), abyssal hill (pelagic) and abyssal plain (turbidite). In carbonate sediments, porosity and density should not be used to predict compressional wave velocity (Morton, 1975) and equations for mean grain size versus compressional wave velocity for continental terrace sediments apply (Johnson et al., 1977). Attenuation of compressional waves in surface sediments is estimated from the equation:

$$\alpha = kf^n \qquad (1)$$

where the exponent n is 1, α is attenuation in dB/m, f is frequency in kHz and k is constant. The constant k is determined for different porosity and mean grain size of sediments from regression equations given by Hamilton (1972, 1976a).

Prediction of shear-wave velocity in surficial sediments, given porosity or mean grain size, is more difficult and tenuous because of the relatively few in situ concurrent measurements of shear-wave velocity and sediment physical properties (Hamilton, 1976b). The development of an in situ shear-wave velocimeter by Shirley and Hampton (1978) should increase our predictive capability. Hamilton (1971a, 1971b) predicted shear-wave velocity in surficial sediments by first constructing bulk density versus sediment bulk modulus (K) and porosity versus sediment bulk modulus graphs. Recent

regression equations for these relationships are given in Morris et al. (1978) for continental terrace sediments and abyssal-hill and abyssal-plain sediments combined. Predicted sediment bulk modulus together with measured or predicted sediment bulk density (ρ) and compressional wave velocity (V_p) are used to predict rigidity or shear modulus:

$$\mu = 3/4\,(\rho V_p^2 - k) \tag{2}$$

Velocity of shear waves is then calculated from bulk density and rigidity:

$$V_s = (\mu/\rho)^{1/2} \tag{3}$$

Sediment bulk modulus can also be predicted if sediment bulk density and compressional wave velocity are known (Morris et al., 1978). Prediction of shear-wave attenuation from porosity, mean-size or bulk-density data is not possible with reasonable accuracy at this time (Hamilton, 1976c).

Rayleigh reflection coefficients and bottom loss of compressional waves at normal incidence to the sediment–water interface can be calculated given impedance of both sediment and water (Hamilton, 1970). Impedance of the sediment can be calculated from bulk density and compressional wave velocity or predicted by the empirical relationship between porosity and impedance or bulk density and impedance. Hamilton (1970) presents these empirical regressions for continental terrace, abyssal-hill and abyssal-plain sediments. Rayleigh reflection coefficients (R) are then calculated from the impedance mismatch:

$$R = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1} \tag{4}$$

where $\rho_1 V_1$ is the impedance of the water and $\rho_2 V_2$ is the impedance of the sediment; bottom loss (BL) is calculated from the Rayleigh reflection coefficient:

$$BL = -20 \log R \tag{5}$$

Rayleigh reflection coefficients and bottom loss can also be predicted directly from porosity or density values using regression equations given by Hamilton (1970).

Physical and acoustic properties of unconsolidated marine sediments are theoretically related by various elastic or viscoelastic models (Hamilton, 1971a, 1974a, b, Stoll, 1974, 1977). This section reviews some of the theoretical relationships between physical, elastic and acoustic properties of sediments to better understand effects of bioturbation on those properties. For the purposes of this paper, Hamilton's (1971a, 1972, 1974b) viscoelastic model is used. Hamilton (1971a) showed when energy damping is low, that one is justified in using Hookean elastic equations to compute various elastic constants (except for attenuation where the viscoelastic equation must be used). Pertinent mathematical relationships include eqs. 1, 2, 3, 6 and 7:

$$V_p = \frac{(K + 4/3\,\mu)^{1/2}}{\rho} \tag{6}$$

$$K = \rho(V_p^2 - 4/3\ V_s^2) \tag{7}$$

where V_p is the velocity of compressional waves (m/sec), K is the bulk modulus (10^{10} dynes/cm^2), μ is the shear modulus (10^{10} dynes/cm^2), ρ is the sediment density (g/cm^3) and V_s is the velocity of shear waves (m/sec).

In unconsolidated marine sediments, shear modulus (dynamic rigidity), shear strength and attenuation are all related to the same sediment factors: friction in sandy sediments and cohesion in silts and clays (Hamilton, 1971a). In sand, the friction between grains is a function of the number of intergrain contacts (related to porosity, mean grain size, sorting, compaction), the surface area of grains, and the interlocking of grains (related to angularity). Rigidity, shear strength and attenuation are increased by lower porosity (given constant grain size), decreased grain size, increased packing and greater angularity (Hamilton, 1972). In silts and clays, cohesion is related to the distance between particles, interparticle bonding and attraction, sediment fabric, clay mineralogy, concentrations of interstitial electrolytes, organic composition and depositional history (Hamilton, 1971a; Young and Southard, 1978). Rigidity, shear strength and attenuation are lower in high-porosity, small-grain sized silts and clays due to the reduction in strength of interparticle attractive forces and reduced interparticle contacts (Hamilton, 1972).

In spite of the obvious relationships between shear modulus, shear strength and attenuation, they are not used to compute one another. Dynamic rigidity is computed from density and shear-wave velocity, shear strength is measured by viscometers or penetrometers, and attenuation is estimated from porosity and mean grain size. Shear-wave velocity is directly related to rigidity and density. Any reduction in rigidity results in a reduction in shear-wave velocity. Shear-wave velocity is also related to the same frictional and cohesive factors controlling shear modulus, shear strength and attenuation.

The bulk modulus or incompressibility of sediments is composed of three separate bulk moduli: (1) the bulk modulus of pore water, (2) the bulk modulus of mineral grains, and (3) bulk modulus of the frame (Hamilton, 1971a) and sediment porosity. The bulk modulus of pore water and of mineral grains varies little in marine sediments; therefore, the contribution of pore-water modulus and mineral-grain modulus to the sediment bulk modulus is primarily dependent on porosity. The frame bulk modulus is dependent on properties and factors influencing sediment fabric, e.g., porosity, grain size, pore-water composition and depositional history. The sediment bulk modulus increases with increasing density, decreasing porosity and increasing grain size (Hamilton, 1971a).

Compressional wave velocity is dependent on incompressibility, rigidity, and density of the sediment. Since the rigidity of most unconsolidated marine sediments is low and sediment density varies little, changes in incompressibility tend to dominate compressional wave velocity.

EFFECTS OF BIOTURBATION ON PHYSICAL PROPERTIES OF SEDIMENTS

Measurements of physical properties of unconsolidated marine sediments, such as those for porosity, bulk density, mean (or median) grain size, cohesion and compaction, are indirect indicators of primary properties of mineral composition, sizes, shapes, orientations and packing of component grains, as well as characteristics of gaseous and fluid substances filling interstitial spaces among the grains. Indirect geotechnical measures of primary properties of sediments are useful for practical engineering applications (Valent, 1974) and have heuristic value regarding behavior of sediments upon being perturbed (Keller, 1974).

It is well known that marine organisms drastically affect all three phases of sediments: the gaseous, liquid and solid. For example, methanogenic bacteria can produce sufficient methane to saturate pore water and form gas bubbles resulting in an acoustically impenetrable bottom (Schubel and Scheimer, 1973). Further, numerous microorganisms (Fenchel, 1969) and deposit-feeding invertebrates (Aller, 1978) have been shown to produce radical changes in pore-water chemistry. Marine organisms, including bivalve molluscs, crustaceans, and fish, are known to alter clay mineralogy by their digestive processes (Anderson et al., 1958; Pryor, 1975). It is beyond the scope of this paper to address the gaseous, liquid and solid phases directly as they are affected by marine organisms. Therefore, we are restricting this discussion to affects of benthic (bottom-dwelling) animals upon the bulk properties of sediments, specifically related to sediment fabric as influencing acoustic properties.

Sediment fabric can be defined simply as the spatial arrangement of component sedimentary particles. The relationship of grain-to-grain contacts is partially understood for silicate and carbonate sands but is poorly understood for cohesive, fine-grained sediments (Richards et al., 1976). Even a fundamental parameter of such great significance as the in situ size of fine-grained sediments is poorly known. In those instances where attempts have been made to measure water-stable aggregates of silty muds, rather than completely disaggregating particles prior to analysis (Folk, 1974), it has been shown that a major portion of the clay- and silt-sized particles are bound into sand-sized, low bulk-density fecal pellets (e.g. Moore, 1931; Rhoads, 1967; Young, 1971). Sediment fabric of clays is influenced by a number of factors, including clay-mineral composition, ionic composition of pore water, amount of pore water, concentration of organic matter and overburden pressure (Meade, 1966). Few studies in which fabric of relatively undisturbed, unconsolidated, marine sediments from nature have been observed via electron microscopy indicate a "loose, open, random arrangement of particles" (Bowles, 1968a). The influence of benthic animals upon preferred orientations of sedimentary particles is not well understood, nor are the altered states of sediments resulting from bioturbation fully comprehended.

The word "bioturbation" (Richter, 1952, in: Schäfer, 1972) from paleontology is used in this paper in the all-inclusive sense of Rhoads (1967),

i.e. "biogenic reworking", as "all biologic activity physically altering sediment". Bioturbation has been shown to influence the following properties of sediments, among others: (a) porosity, median grain size, and bulk density, (b) compaction and cohesion, (c) particle orientation and distribution, and (d) microtopography. These properties are discussed separately.

Porosity, median grain size and bulk density

Porosity and median grain size increase markedly and bulk density decreases as a result of bioturbation (Rhoads and Young, 1970; Young, 1971). Increased porosity and median grain size result primarily from increasing overall pore space and sediment particle size by the binding of small constituent particles of clay- and silt-sized sediment into sand-sized fecal pellets by benthic animals. Bulk density decreases as a result of greater proportion of low-density pore water to higher-density sediment. The fecal pellets themselves may have high porosity[1], i.e., 80% (Risk and Moffat, 1977). Highly bioturbated muds may reach 92% porosity (Rhoads, 1974). The upper several centimeters of abyssal sediments, which are intensively reworked by deep-sea benthic animals, range from 60 to 90% porosity (Hollister et al., 1975).

Compaction and cohesion

Compaction and cohesion of marine sediments are measured in situ by rotational viscometers (e.g. T-bar spindles, vane shears) and by penetrometers. These measures are directly related to one another and indirectly related to porosity and bulk density. Cohesive muds have high erosional resistance because of electrochemical interparticle bonding and organic binding (Van Olphen, 1966). Highly bioturbated, i.e., pelletized, muds at the sediment–water interface have little cohesive strength (Bokuniewicz et al., 1975) and are easily eroded (Rhoads and Young, 1970). Shear strength of a silty mud sediment has been shown to increase from 10 g/cm^2 to more than 18 g/cm^2 as successive vane shear measurements were taken 20 cm away to immediately adjacent to a membranous tube of a burrowing anemone (Rowe, 1974). Myers (1977) has demonstrated both increases and decreases in shear strength of a sandy sediment resulting from bioturbation by two different species of benthic animals. Richards and Parks (1976) have attributed high variance of shear-strength measurements of sediments in a Norwegian fjord to effects of bioturbation. Clearly, the resulting fabric of sediments at any given time represents a balance of predominating influences of bioturbation by different species. An open fabric from ingestion/defecation/pelletizing activities of mobile deposit feeders results in low compaction and cohesion, whereas a compacted, cohesive and tight fabric results from extensive burrowing and tube-building (Rhoads, 1974).

[1] All sediment water content values are presented as percent porosity in this paper. Where necessary, percent water content (in sensu Rhoads, 1974, or Keller, 1974) were recalculated assuming a mineral grain density of 2.650 g/cm^3 and a water density of 1.024 g/cm^3.

Particle orientation and distribution

Bioturbation produces either homogeneous fabric, i.e., random particle orientation and random size distribution, or heterogeneous fabric, i.e., aggregations of grain sizes and compositions (Rhoads, 1974). As previously discussed, effective particle size may be increased by pelletizing activities. In addition, individual grains may be selectively ordered and segregated within fecal pellets in terms of size and composition (Pryor, 1975). Selective feeding upon small particles by deposit-feeding animals results in graded bedding (Rhoads, 1967), X-radiographic opaque layers of denser grains (Rhoads and Young, 1970) and water-filled voids within the sediment fabric (Rhoads and Young, 1971).

Microtopography

Bioturbation produces microtopography of the sea floor. Heezen and Hollister (1971) have suggested that the visually dominant benthic animals on the deep-sea floor, the holothurians, produce "... features more widespread and more visibly evident than those produced by any other animal on earth" by their extensive sediment reworking activities. Mounds, depressions, trails and burrows, i.e., "Lebensspuren", leading to preserved trace fossils upon lithification have been subjected to intensive study for decades (Schäfer, 1972; Frey, 1975). In contrast, the importance of biogenically produced microtopography in generating increased bottom roughness, thereby contributing to increased turbulence at the sea floor and increased resuspension of reworked particles, has not been fully appreciated (Rhoads, 1974).

Bioturbation activity decreases rapidly below the upper 10 cm layer of most unconsolidated marine sediments (Rhoads, 1974), although certain benthic animals have been known to burrow several meters deep (Myers, 1979). Depths of reworking activity in deep-sea sediments, as measured by the distribution of certain radionuclides, range from 10 to 60 cm (Guinasso and Schink, 1975). Since burrows are readily recognizable "Lebensspuren" they are commonly recorded from deep-sea cores (Chamberlain, 1975; Berger et al., 1979). Electron microscopic examinations of epoxy-resin-impregnated thin-sections of continental-slope sediments have demonstrated clustering of randomly oriented particles and very large voids attributable to extensive burrowing activity (Bowles, 1968b). Evidence of quasifluid deformation, i.e., false-bodied thixotropy, of sediments by benthic animals is preserved in the fossil record (Rhoads, 1970), contrary to the contention of Elliott (1965). False-bodied thixotropy, which is a fluid property of a sediment, is produced by biogenic modifications leading to decreases in compaction and increases in porosity, as previously discussed. This type of biogenic deformation of sediment structure, although not as readily recognizable as that resulting from burrowing and tube-building, is widespread in silty mud sediments and may be responsible, in part, for the open cardhouse or honeycomb sediment fabric reported by Bowles (1968a).

PREDICTED EFFECTS OF BIOTURBATION ON ACOUSTIC PROPERTIES OF SEDIMENTS

It has been shown that acoustic properties of sediments are empirically predicted as well as theoretically determined by physical properties of sediments. It has also been shown that most, if not all, physical properties of sediments which are important to geoacoustic models (e.g., porosity, grain size, density, fabric, rigidity or shear modulus, and incompressibility or bulk modulus) are regulated by or at least altered by bioturbation by benthic animals. We therefore hypothesize that *bioturbation by benthic animals alters the acoustic properties of unconsolidated marine sediments.*

In order to predict the magnitude of effects of bioturbation on marine sediments, we calculated the affects of *Nucula annulata*, a protobranch bivalve (Fig.1), on acoustic and elastic properties of sediments. *N. annulata* is a common deposit-feeding bivalve found at station "R" in Buzzards Bay, Massachusetts (Hampson, 1971). The sediment at station "R" is primarily silt- and clay-sized particles (78–91%, mean grain size 6 ϕ) as determined by standard geological grain-size analysis (Sanders, 1960). The intensive sediment reworking by *N. annulata* creates an uncompacted granular sediment surface (Fig.2) consisting of sand-sized fecal pellets of low bulk density (Young, 1971). The porosity of near-surface reworked[2] station "R" sediment was as high as 86% compared to 70% porosity for unreworked station "R" sediment (Rhoads and Young, 1971).

The velocity of compressional waves in bioturbated and nonbioturbated sediments was calculated from Hamilton's (1974) predictor equation for continental terrace sediments:

$$V_p = 2455.9 - 21.716(\eta) + 0.126(\eta)^2 \tag{8}$$

where V_p is compressional wave velocity (m/sec) and η is porosity (%). The calculated compressional wave velocities were then corrected for the 20 m water depth, 20°C bottom temperature and 30‰ salinity at station "R" using Wilson's (1962) equations for the speed of sound in sea water (Hamilton, 1971). Bioturbation by *N. annulata* increased porosity, which decreased compressional wave velocity from 1547 m/sec to 1514 m/sec (Table I).

The attenuation of compressional waves (α = dB/m) in bioturbated and nonbioturbated sediments was calculated from the regression equation:

$$\alpha = 0.7602 - 0.01487(\eta) + 0.000078(\eta)^2 f \tag{9}$$

where η is porosity (%) and f is frequency (3.5 Khz) (Hamilton, 1972). Compressional waves were attenuated less in bioturbated sediment than in sediment unaffected by bioturbation (Table I).

Bottom loss (*BL*) and Rayleigh reflection coefficients of compressional waves at normal incidence to the sediment–water interface can be calculated

[2] The term "reworked" is used synonymously here with "bioturbated".

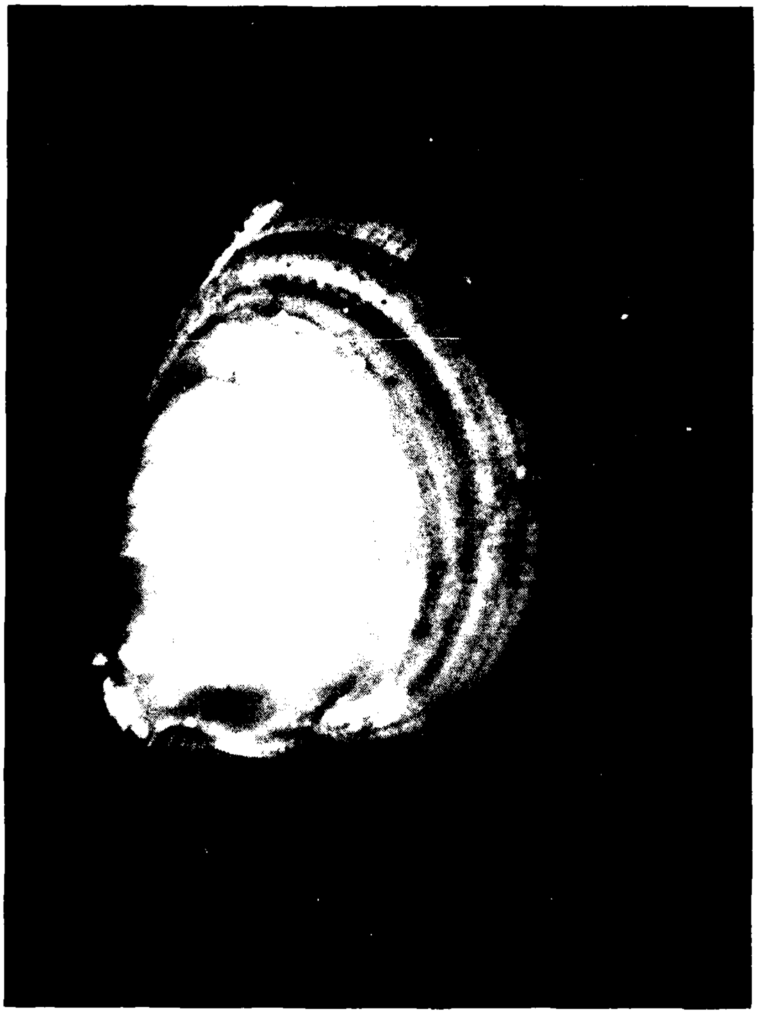
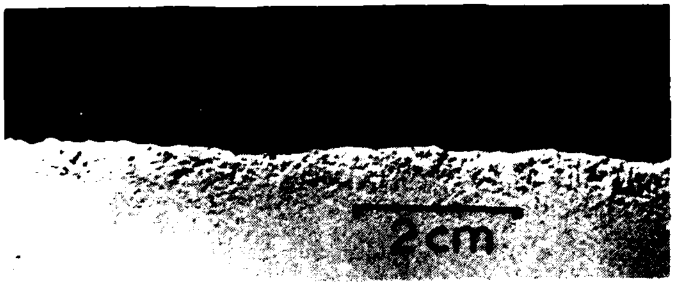


Fig.1. *Nucula annulata*, a common deposit feeding bivalve found at Station "R" in Buzzards Bay, Massachusetts.

from porosity--impedance relationships given by Hamilton (1970) or compressional wave velocity times density formulae. The graphical and computational values were the same for each sediment type. The impedance of bioturbated (1.89 g/cm^2 sec $\cdot$ 10^5) sediment was lower than nonbioturbated (2.23 g/cm^2 sec $\cdot$ 10^5) sediment. The Rayleigh reflection coefficient calculated from impedance values of bioturbated sediment and sea water was 0.10, resulting in a 20 dB bottom loss for compressional wave at normal incidence to the sediment—water interface. The sediment which was not bioturbated had a calculated Rayleigh reflection coefficient of 0.20 and a 14 dB bottom loss.



A

B

Fig.2. A. In situ photograph of reworked sediment at Station "R" Buzzards Bay, Massachusetts (from Young, 1971). B. Photograph of Buzzards Bay sediments reworked by *Nucula annulata* in the laboratory (from Young, 1971).

The incompressibility (K) or bulk modulus was estimated using Hamilton's (1971a) graphical relationship between bulk modulus and porosity for continental terrace sediments. The bioturbated sediment had a lower bulk modulus and was therefore more easily compressed than sediment which was not bioturbated (Table I). The rigidity or shear modulus (μ) was calculated from eq.2. The bioturbated sediment had a lower calculated rigidity than the nonbioturbated sediment (Table I).

The shear wave velocity (V_s) was calculated from eq.3 from Hamilton (1971a). The velocity of shear waves was 325 m/sec in nonbioturbated sediment and 179 m/sec in bioturbated sediment. Although not calculated, the attenuation of shear waves in higher-porosity bioturbated sediment would be lower than the attenuation in lower-porosity nonbioturbated sediment (Hamilton, 1976c).

TABLE I

Calculated relationships of Station "R" (Buzzards Bay, Massachusetts) sediments bioturbated by *Nucula annulata* and not bioturbated (porosity, temperature and water depth from Rhoads and Young, 1970)

	Nonbioturbated	Bioturbated
Porosity	70%	86%
Temperature	20°C	20°C
Water depth	20 m	20 m
Density of sediment grains	2.65 g/cm^3	2.65 g/cm^3
Density of water	1.021 g/cm^3	1.021 g/cm^3
Density of sediment	1.51 g/cm^3	1.25 g/cm^3
Velocity of compressional wave	1547 m/sec	1514 m/sec
Attenuation at 3.5 khz	0.35 dB/m	0.20 dB/m
Impedance of sediment	2.33 g/cm^2 sec $\cdot 10^5$	1.89 g/cm^2 sec $\cdot 10^5$
Rayleigh reflection coefficient	0.20	0.10
Bottom loss	14 dB	20 dB
Bulk modulus	$3.4 \cdot 10^{10}$ dynes/cm^2	$2.8 \cdot 10^{10}$ dynes/cm^2
Shear modulus	$0.16 \cdot 10^{10}$ dynes/cm^2	$0.04 \cdot 10^{10}$ dynes/cm^2
Velocity of shear wave	325 m/sec	179 m/sec

In summary, we calculated that bioturbation by *N. annulata* decreased velocity and attenuation of compressional and shear waves in sediments while increasing bottom loss at the sediment–water interface. We then addressed the question: "Do the calculated changes in acoustic and elastic properties of sediment bioturbated by *N. annulata* agree with the theoretical relationships between physical, elastic and acoustic properties of sediment presented by Hamilton (1971a)?"

N. annulata, by packaging silt- and clay-sized particles into sand-sized particles, in the form of rod-like fecal pellets, created a poorly sorted sediment with a lower number of grain-to-grain contacts and a more open fabric. This process resulted in lower bulk density and higher porosity of sediment. The sediment would be expected to have reduced cohesion because of the open fabric and reduced grain-to-grain contact. It follows from Hamilton (1971a) that reduced cohesion would result in reduced shear modulus (rigidity) of bioturbated sediment. Rhoads (1974), using penetrometers to measure sediment hardness, confirmed that sediment reworked by *N. annulata* had lower shear strength, thus lower cohesion, than sediment not bioturbated by *N. annulata*.

Although bioturbation can change characteristics of both pore water and mineral grains (see previous section), the greatest effects of bioturbation on sediment bulk modulus are the effects on frame bulk modulus and porosity. We know of no direct or indirect measure of bulk modulus made on sediment bioturbated by *N. annulata*. It is logical that a higher-porosity, open-fabric, bioturbated sediment would be more easily compressed than a lower-porosity

sediment with a greater number of grain-to-grain contacts. The poorly sorted bioturbated sediment would also have higher permeability and decreased incompressibility.

The calculated values of rigidity and incompressibility and the measured value of bulk density agree with what is known about the effects of bioturbation by *N. annulata* on sediments. Since the acoustic properties of sediments can be used to calculate the elastic properties of sediments, the predicted relationships between bioturbation and the elastic and acoustical properties of sediments can be tested by measuring the velocity of compressional waves in bioturbated and unbioturbated sediments in laboratory experiments. We will report the results of these experiments in a later paper.

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REFERENCES

Aller, R.C., 1978. Experimental studies of changes produced by deposit feeders on pore water, sediment, and overlying water chemistry. Am. J. Sci., 278: 1185–1234.

Anderson, A.E., Jonas, A.E. and Odum, J.T., 1958. Alteration of clay minerals by digestive processes of marine organisms. Science, 127: 190–191.

Berger, W.H., Ekdale, A.A. and Bryant, P.F., 1979. Selective preservation of burrows in deep-sea carbonates. Mar. Geol., 32: 205–230.

Bokuniewicz, H.J., Gordon, R. and Rhoads, D.C., 1975. Mechanical properties of the sediment water interface. Mar. Geol., 18: 263–278.

Bowles, F.A., 1968a. Microstructure of sediments: investigation with ultra-thin sections. Science, 159: 1236 1237.

Bowles, F.A., 1968b. Electron Microscopy Investigation of the Microstructure in Sediment Samples from the Gulf of Mexico. Ph.D. dissertation, Texas A&M University, College Sta., Texas, 133 pp.

Chamberlain, C.K., 1975. Trace fossils in DSDP cores of the Pacific. J. Paleontol., 49: 1974 1996.

Elliott, R.E., 1965. A classification of subaqueous sedimentary structures based on rheological and kinematical parameters. Sedimentology, 5: 193.

Fenchel, T., 1969. The ecology of marine microbenthos, IV. Structure and function of the benthic system, its chemical and physical factors and the microfauna communities with special reference to the ciliated protozoa. Ophelia, 6: 1 182.

Folk, R.J., 1974. Petrology of Sedimentary Rocks. Hemphill, Univ. Texas, Austin, 154 pp

Frey, R.W., 1975. The realm of ichnology, its strengths and limitations. In: R.W. Frey (Editor), The Study of Trace Fossils. Springer, New York, N.Y., pp.13 38.

Guinasso, N.L. and Schink, D.R., 1975. Quantitative estimates of biological mixing rates in abyssal sediments. J. Geophys. Res., 80: 3032 3043.

Hamilton, E.L., 1956. Low sound velocities in high-porosity sediments. J. Acoust. Soc. Am., 28: 16 19.

Hamilton, E.L., 1963. Sound velocity measurements made in situ from bathyscaph Trieste. J. Geophys. Res., 68: 5991–5998.

Hamilton, E.L., 1970. Reflection coefficients and bottom losses at normal incidence computed from Pacific sediment properties. Geophysics, 35: 995–1004.

Hamilton, E.L., 1971a. Elastic properties of marine sediments. J. Geophys. Res., 76: 579–603.

Hamilton, E.L., 1971b. Prediction of in-situ acoustic and elastic properties of marine sediments. Geophysics, 36: 266–284.

Hamilton, E.L., 1972. Compressional wave attenuation in marine sediments. Geophysics, 37: 620–646.

Hamilton, E.L., 1974a. Prediction of deep-sea sediment properties: state-of-the-art. In: A.L. Inderbitzen (Editor), Deep-Sea Sediments: Physical and Mechanical Properties. Plenum Press, New York, N.Y., pp.1–43.

Hamilton, E.L., 1974b. Geoacoustic models of the sea floor. In: L. Hampton (Editor), Physics of Sound in Marine Sediments. Plenum Press, New York, N.Y., pp.181–221.

Hamilton, E.L., 1976a. Sound attenuation as a function of depth in the sea floor. J. Acoust. Soc. Am., 59: 528–535.

Hamilton, E.L., 1976b. Shear-wave velocity versus depth in marine sediments: a review. Geophysics, 41: 985–996.

Hamilton, E.L., 1976c. Attenuation of shear waves in marine sediments. J. Acoust. Soc. Am., 60: 334–338.

Hamilton, E.L., Schumway, G., Menard, H.W. and Shipek, C.J., 1956. Acoustic and other physical properties of shallow-water sediments off San Diego. J. Acoust. Soc. Am., 28: 1–15.

Hampson, G.R., 1971. Species pair of the genus *Nucula* (Bivalvia) from the eastern coast of the United States. Proc. Malacol. Soc., London, 39: 333–342.

Heezen, B.C. and Hollister, C.D., 1971. The Face of the Deep. Oxford Univ. Press, New York, N.Y., 659 pp.

Hollister, C.D., Heezen, B.C. and Nafe, K.E., 1975. Animal traces on the deep-sea floor. In: R.W. Frey (Editor), The Study of Trace Fossils. Springer, New York, N.Y., pp.493–510.

Johnson, T.C., Hamilton, E.L. and Berger, W.H., 1977. Physical properties of calcareous ooze: control by dissolution at depth. Mar. Geol., 24: 259–277.

Keller, G.H., 1974. Marine geotechnical properties: Interrelationships and relationships to depth of burial. In: A.L. Inderbitzen (Editor), Deep-Sea Sediments: Physical and Mechanical Properties. Plenum Press, New York, N.Y., pp.77–100.

Meade, R.H., 1966. Factors influencing the early stages of the compaction of clays and sands — review. J. Sediment. Petrol., 36: 1085–1101.

Moore, H.B., 1931. The muds of the Clyde Sea area. III. Chemical and physical conditions, rate and nature of sedimentation, and fauna. J. Mar. Biol. Assoc. U.K., 17: 325–358.

Morris, H.E., Hamilton, E.L., Bucker, H.P. and Bachman, R.T., 1978. Interaction of sound with the ocean bottom: a three-year summary. Naval Ocean System Cent. Tech. Rep., 242: 77 pp.

Morton, R.W., 1975. Sound velocity in carbonate sediments from the Whiting Basin, Puerto Rico. Mar. Geol., 19: 1–17.

Myers, A.C., 1977. Sediment processing in a marine subtidal sandy bottom community. I. Physical aspects. J. Mar. Res., 35: 609–632.

Myers, A.C., 1979. Summer and winter burrows of a mantis shrimp, *Squilla empusa*, in Narragansett Bay, Rhode Island (U.S.A.). Estuar. Coast. Mar. Sci., 8: 87–98.

Nafe, J.E. and Drake, C.L., 1957. Variation with depth in shallow and deep-water marine sediments of porosity, density and the velocities of compressional and shear waves. Geophysics, 22: 523–552.

Nafe, J.E. and Drake, C.L., 1963 Physical properties of marine sediments. In: M.N. Hill (Editor), The Sea, III. Interscience, New York, N.Y., pp. 794–815.
Pryor, W.A., 1975. Biogenic sedimentation and alteration of argillaceous sediments in shallow marine environments. Geol. Soc. Am. Bull., 86: 1244–1254.
Rhoads, D.C., 1967. Biogenic reworking of intertidal and subtidal sediments in Barnstable Harbor and Buzzards Bay, Massachusetts. J. Geol., 75: 461–476.
Rhoads, D.C., 1970. Mass properties, stability, and ecology of marine muds related to burrowing activity. In: T.P. Crimes and J.C. Harper (Editors), Trace Fossils. Geol. J. Spec. Issue, 3: pp.391–406.
Rhoads, D.C., 1974. Organism–sediment relations on the muddy sea floor. Oceanogr. Mar. Biol. Am. Rev., 12: 263–300.
Rhoads, D.C. and Young, D.K., 1970. The influence of deposit-feeding organisms on sediment stability and community trophic structure. J. Mar. Res., 28: 150–178.
Rhoads, D.C. and Young, D.K., 1971. Animal–sediment relations in Cape Cod Bay, Massachusetts, II. Reworking by *Molpodia oolitica* (Holothuroides). Mar. Biol., 11: 225–261.
Richards, A.F. and Parks, J.M., 1976. Marine geotechnology. Average sediment properties, selected literature and review of consolidation, stability, and bioturbation–geotechnical interactions in the benthic boundary layer. In: I.N. McCave (Editor), The Benthic Boundary Layer. Plenum Press, New York, N.Y., pp.157–181.
Richards, A.F., DeVries, M., Einsele, C., Komar, P.D., Krone, R.B., Owen, N.W., Southard, J.B., Spiess, F.N., Taylor-Smith, D., Terwindt, T. and Keller, G.H., 1976. Sea-floor deposition, erosion, and transportation. In: I.N. McCave (Editor), The Benthic Boundary Layer. Plenum Press, New York, N.Y., pp.247–260.
Risk, M.J. and Moffat, J.S., 1977. Sedimentological significance of fecal pellets of *Macoma balthica* in the Minas Basin Bay of Fundy. J. Sediment. Petrol., 47: 1425–1436.
Rowe, G.T., 1974. The effects of the benthic fauna on the physical properties of deep-sea sediments. In: R.L. Inderbitzen (Editor), Deep-Sea Sediments: Physical and Mechanical Properties. Plenum Press, New York, N.Y., pp.381–400.
Sanders, H.L., 1960. Benthic studies in Buzzards Bay, III. The structure of the soft bottom community. Limnol. Oceanogr., 5: 138–153.
Schäfer, W., 1972. Ecology and Palaeoecology of Marine Environments. Univ. Chicago Press, Illinois, 568 pp.
Schubel, J.R. and Scheimer, E.W., 1973. The cause of the acoustically impenetrable or turbid character of Chesapeake Bay sediments. Mar. Geophys. Res., 2: 61–71.
Shirley, D.J. and Hampton, L.D., 1978. Shear-wave measurements in laboratory sediments. J. Acoust. Soc. Am., 63: 607–613.
Stoll, R.D., 1974. Acoustic waves in saturate and sediments. In: L. Hampton (Editor), Physics of Sound in Marine Sediments. Plenum Press, New York, N.Y., pp.19–40.
Stoll, R.D., 1977. Acoustic waves in ocean sediments. Geophysics, 42: 715–725.
Sutton, G.H., Berckhomer, H. and Nafe, J.E., 1957. Physical analysis of deep-sea sediments. Geophysics, 22: 779–812.
Valent, P.J., 1974. Deep-sea foundation and anchor engineering. In: A.L. Inderbitzen (Editor), Deep-Sea Sediments: Physical and Mechanical Properties. Plenum Press, New York, N.Y., pp.245–269.
Van Olphen, H., 1966. An Introduction to Clay Colloid Chemistry. Interscience, New York, N.Y., 301 pp.
Wilson, W.D., 1962. Table of Sound Speed in Sea Water. U.S. Naval Oceanogr. Off. Spec. Publ., 58: 47 pp.
Young, D.K., 1971. Effects of infauna on the sediment and seston of a subtidal environment. Vie Milieu Suppl., 22: 557–571.
Young, R.N. and Southard, J.B., 1978. Erosion of fine-ground marine sediments: sea-floor and laboratory experiments. Geol. Soc. Am. Bull., 89: 663–672.